Single particle damage events in candidate star camera sensors

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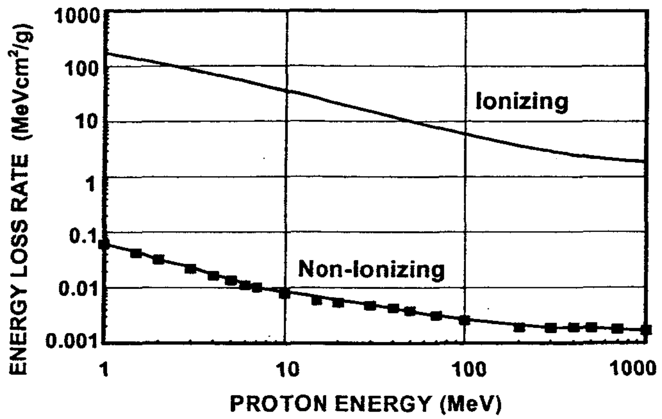
Outline

- Solar and trapped protons and shielding
  - Energy range and mechanisms
- Proton interactions in Si
  - Ionization (Total Ionizing Dose – TID)
  - Displacement damage (trapping and increased leakage)
  - Single event transient effects – important but not covered here
- Displacement damage effects in detectors
  - Dark current dependence on temperature
  - "Universal" damage constant for "bulk" dark current
  - Damage distributions, hot pixels & random telegraph noise
  - Electric field enhancement of leakage currents
- Hot pixel mechanisms, introduction rates, and annealing
  - On-orbit HST measurements
  - Laboratory measurements (WFC3 CCDs)
  - Implications for star camera applications: CCDs, APS, CIDs, hybrids

Proton Energy Loss Mechanisms in Si: Ionization (LET) and Displacements (NIEL)

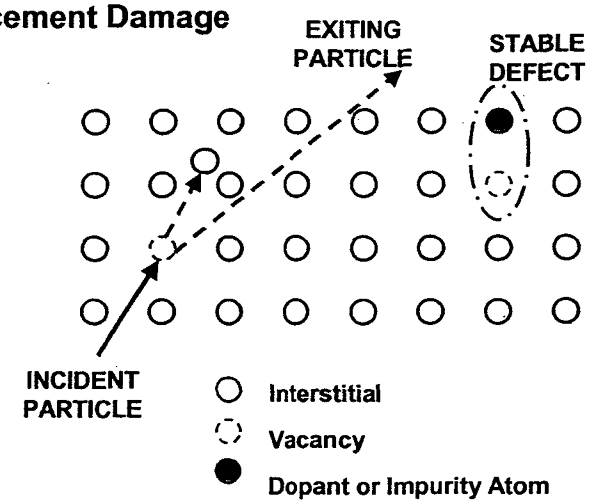


Nonionizing energy loss correlates with displacement damage as LET does with ionizing dose (rads(Si))

C.J. Dale et al., "A Comparison of Monte Carlo and Analytic Treatments of Displacement Damage in Microvolumes, IEEE TNS, Vol. 41, 1994.

Evolution of Initial Vacancy-Interstitial Pairs to Stable Defects

Displacement Damage

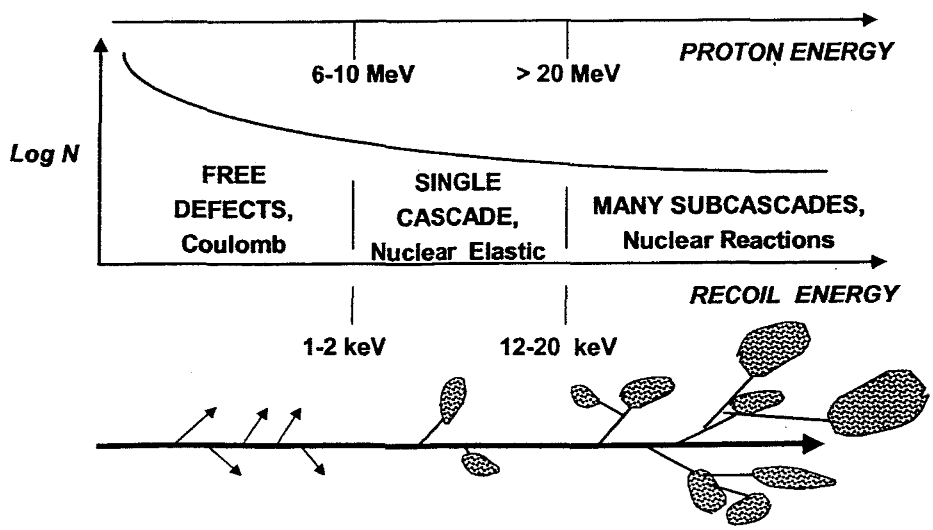


- Stable divacancy complex defects may also form and are important for dark current generation

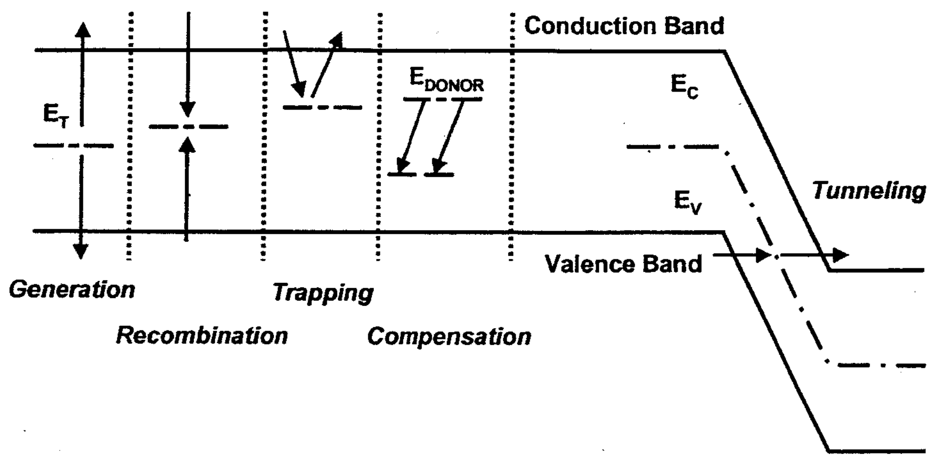
Proton Spectra Behind Thick Shields

- Trapped proton environment decreases exponentially with energy and is populated out to ~ 400 MeV
- Lower energy protons are stopped more easily, but all protons lose energy when transported through shield
- Behind ~ 1 inch Al, the average proton energy is >80 MeV
  - ➢Relatively few protons below ~ 30 MeV
- Need to anticipate the damage mechanisms for higher energy protons (> 50 MeV)

Displacement Damage Processes in Si



Electrical Effects of Proton-Induced Defects



Dark Current and Temperature

$$J_d, K_{dark} \propto e^{(-E_{act}/kT)}$$

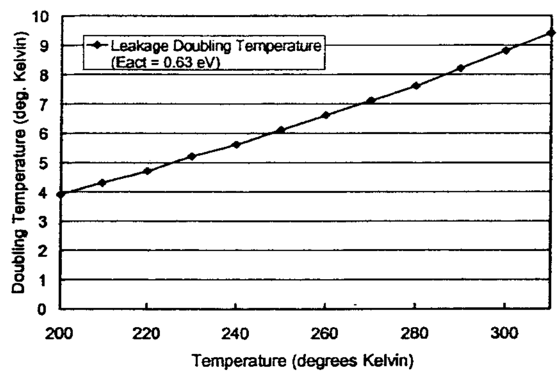
J_d is bulk leakage or dark current: not FET leakage

K_{dark} is damage factor

E_{act} is activation energy
E_{act} = 0.63 eV [1]

k is Boltzman's constant
k = 8.62 E-05 eV/T

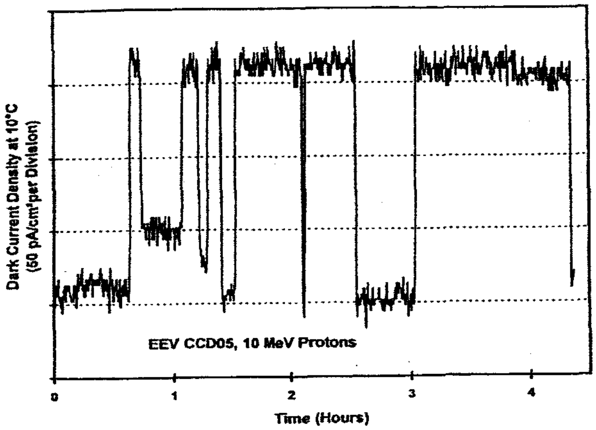
T is Temperature in Kelvin



Srour and Lo find that proton induced leakage from a variety of studies exhibit an activation energy of from 0.62 to 0.64 eV, and 0.63 works well for both pre and post radiation

[1] "Universal Damage Factor for Radiation-Induced Dark Current in Si Devices," J.R. Srour and D.H. Lo, IEEE Trans. Nucl. Sci., NS-47, No. 6, Dec. 2000, pp. 2451-59

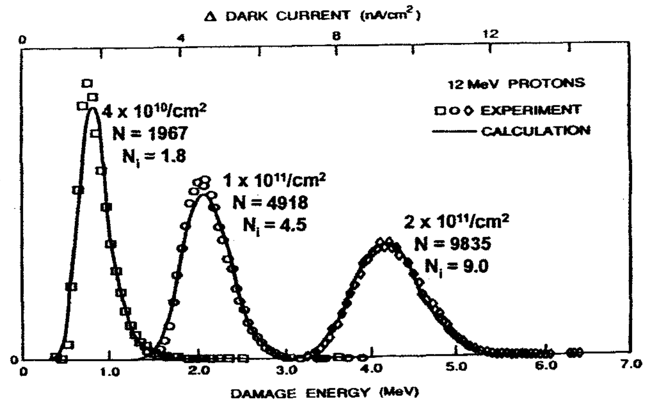
Temporal Dark Current Fluctuations in a Pixel



- Same phenomena seen in APS, CID's and other diode structures
- Shot noise assumptions for leakage currents may be too optimistic

I.H. Hopkins and G.R. Hopkinson, "Random Telegraph Signals from Proton-Irradiated CCDs," IEEE TNS, Vol. 40, No. 6, pp. 1567-1574, 1993.

Pixel-to-Pixel Dark Current Nonuniformities (2)

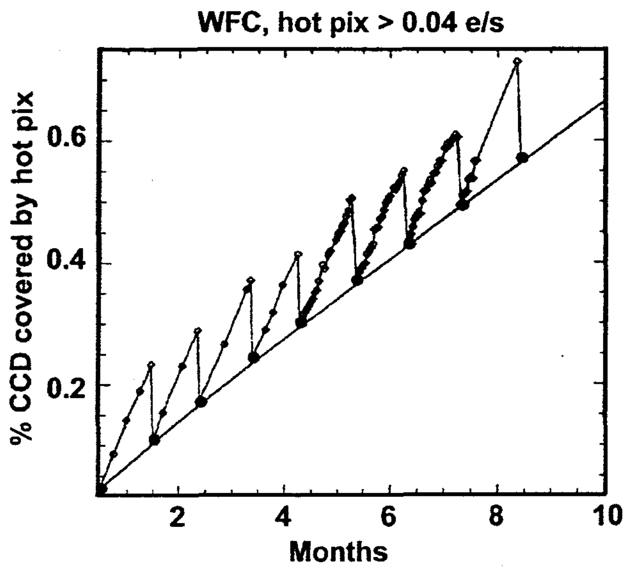


- **Nonuniformity Can Be Significant Concern**
- **Measurements at 293° Kelvin**
- **High Energy Tails Due to Statistics of Nuclear Reactions**

•CID Pixel volume is 1300 cubic microns: or ~1/8th of reference volume after roughly 40 krad(Si) damage for highest damage level shown, so consider ~300 nA/cm² at room temperature and ~258° K to reach 10 nA/cm² for the average J_d
•Expect more broadening of distribution due to higher proton energies

P.W. Marshall, et al., "Proton-Induced Displacement Damage Distributions and Extremes in Silicon Microvolumes," IEEE Trans. On Nucl. Sci, NS-37, No. 6, 1990.

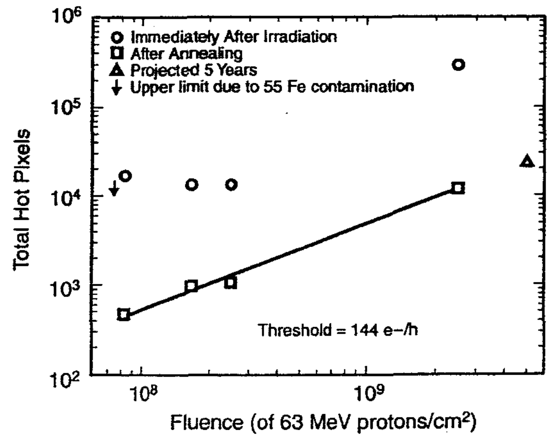
HST Hot Pixels – on Orbit Annealing



- Accumulation of hot pixels mandates monthly warm-ups to ~0C
- Similar annealing results observed in 3 HST instruments
- 1st laboratory measurements made for WFC3

WFC3 Hot Pixel Experiment (1)

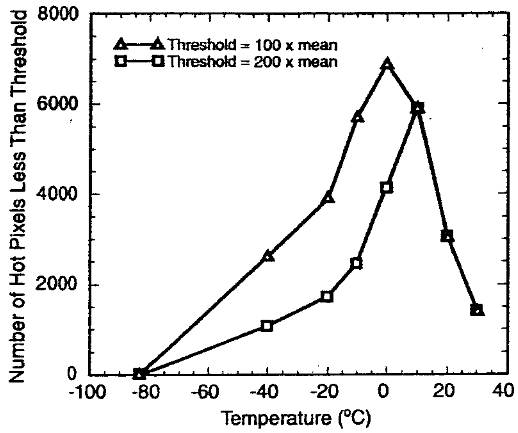
- A Hubble Space Telescope Wide Field Camera 3 E2V CCD was irradiated while operating at -83 °C and the dark current studied as a function of temperature while the CCD was warmed up to a +30°C.
- Populations of hot pixels (defined as pixels having more than a given dark current threshold) were tracked to identify whether a hot pixel encountered at any fluence is a new hot pixel or an existing one.



WFC3 Hot Pixel Experiment (2)

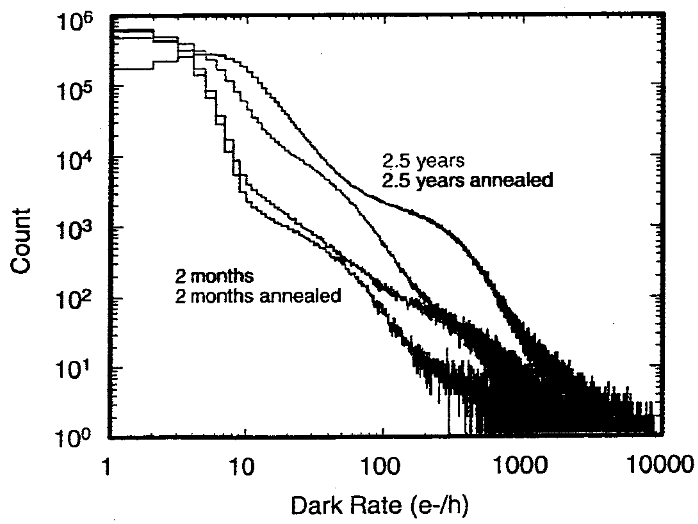
- Hot pixel populations tracked during warm-up and cool-down. Annealing process underway by -40C and continues through warmer temperatures with no sharp activation energy.

- The peak annealing rate at 0°C is an artifact caused by the saturation of hot pixels.



WFC3 Hot Pixel Experiment (3)

- Mean dark current slightly elevated, but still less than 2 e-/h
- Shape of tails changing
- Annealed hot pixels become warm pixels



Implications for Tracker Performance

- Depending on the application either CTE (for CCDs) or dark current can be the driving radiation effect.
- Hot pixels may be caused by small (Coulomb) events in high field regions and by rare nuclear reactions.
    - Observed in CCDs, CIDs, APS and Si hybrid devices
- If your tracker is cooled (even modestly) then you will underestimate the number of hot pixels by following usual proton test procedures at room temperature.
    - This can overwhelm the capacity of the tracker software.